NAVAL AIR DEVELOPMENT CENTER

Johnsville, Warminster, Pennsylvania

REPORT NO. NADC-AC-7003 16 April 1970

EXPERIMENTAL SYSTEMS FOR IMPACT PROTECTION

INTERIM REPORT

AIRTASK A31310/202/70R0050101, WORK UNIT 1

P R E P A R E D B Y

THE FRANKLIN INSTITUTE RESEARCH LABORATORIES
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DEPARTMENT OF THE NAVY
NAVAL AIR DEVELOPMENT CENTER
JOHNSVILLE
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Aerospace Crew Equipment Department

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(Final Report on Contract N00156-70-C1192)

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The impact absorbing properties of starch/brine dilatant suspensions were characterized with an instrumented, pendulum-type impact tester The starch concentrations were varied between 47.5 and 52.5% and sealed in heavy rubber bags of varying thickness. The temperature of the filled rubber bags was varied between 45° and 110°F Impacting energies ranged between 30 and 141 ft-lbs with velocities of 11 and 17 ft/sec. The dilatant suspensions were found to be highly efficient and reusable energy absorbers under all test conditions Impactor penetration, peak deceleration, and jerk varied depending on the impact energy input, impact velocity, bag wall thickness, and, to a lesser extent, starch concentration and temperature. The filled bags readily conform to the shape of a 1 cm radius impactor and yield relatively low peak deceleration and jerk. There was no noticeable deterioration of the dilatant properties as a result of temperature cycling and repeated impacts.

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1. INTRODUCTION

In an effort to discover better energy absorbing materials for use as human body-machine interfaces dilatant slurries have been suggested by the Franklin Institute Research Laboratories. Dilatant slurries or suspensions are typically composed of particles dispersed in high concentration in a fluid medium. At low rates of applied loading the suspension flows easily with a low apparent viscosity, but above some critical loading rate the resistance to flow, i.e. the viscosity, increases markedly.[1,2,3] The property of flow dilatancy should be particularly useful for aircraft ejection seat cushions. Under normal flight conditions the loading rates would be low and the cushion would remain compliant and comfortable. On ejection however, the cushion would become "stiff" due to the increased loading rate, allowing the pilot to experience only a slightly higher acceleration than the seat frame. Experience[4] has shown that highly compliant cushions collapse during ejection causing the ejectee to experience magnified acceleration forces and increased likelihood of injury when the cushion "bottoms". A potential addition benefit of a dilatant cushion is that the dilatant suspension in the pseudo-solid condition may exhibit crushability and thereby become an effective impact energy absorber.

The particular dilatant suspension system studied in this program is a starch-water mixture. The mixture was poured and sealed into heavy rubber bags which act as elastically deformable containers and the response to energy input was measured by using an instrumented pendulum. The starch concentration and bag temperature were varied along with the bag wall thickness and energy input. This report discusses the results of these tests and the methods used to obtain them.

2. INSTRUMENTATION

The primary piece of equipment used for all tests was a modified Wiedemann-Baldwin Model SI-I Impact Tester. The impact tester is normally meant to test the breaking strength of metal or plastic specimens by use of a free swinging, weighted pendulum. For the testing of the suspension-filled rubber bags the impact tester was modified in three ways:

(1) A heavy steel backstop was provided for the suspension-filled rubber bag. The bags were then suspended by a string at the lowest point in the path of the pendulum. The spacing was such that when the pendulum was at rest there were 3 inches between the face of the pendulum and the backstop - the approximate thickness of a filled bag. The arrangement of the backstop, rubber bag and pendulum is shown in Figure 1.

Fiaure 1. Arranqement of Backstop, Rubber Baq and Pendulum.

(2) The pendulum bob was fitted with a steel face plate on which an Endevco Model 2225 piezoelectric accelerometer was mounted as shown in Figure 2. The face plate was 5/8" thick so that it would behave as a relatively rigid surface upon impact with a test specimen. The accelerometer has the characteristics listed in Table 1 and adequately responds to the dynamic decelerations to which the pendulum is subjected during impact. The output signal from the Endevco accelerometer was fed to a Kistler Model 503 charge amplifier and then to one channel of a Tektronix 454/R454 oscilloscope for viewing and recording.

TABLE 1

Accelerometer Characteristics
Endevco Model 2225 (S/N LB62)

Charge sensitivity = 0.590 peak picocoulombs/peak-g

Resonant Frequency = 30 kilohertz

Frequency range = 1 hertz to 6 kilohertz

(3) A precision wire wound potentiometer (Helipot Model SL277, 10K) was mounted on the pivotal axis of the pendulum so that the depth of penetration of the pendulum face into the test specimen and the rebound angle of the pendulum (after striking the specimen) could be recorded. Figure 3 shows the location of the potentiometer. Figure 4 shows the method of wiring the potentiometer to the second channel of the Tektronix 454/R454 oscilloscope and a Sanborn chart recorder. The oscilloscope was used to observe and record the depth of penetration of pendulum into a test specimen (accuracy is within 0.1"); the chart recorder is used to record the rebound angle (accuracy is within 1°). A BLH constant voltage, d-c supply provides voltage across the potentiometer. As shown in Figure 4 both the depth of penetration and the deceleration of the pendulum are displayed simultaneously as dual traces on the oscilloscope. These two signals are swept horizontally usually at the rate of 5 milliseconds per centimeter (screen width is 10 centimeters). The horizontal sweep is triggered by the output pulse from an Abtronics Model 500 Transient Light Detector. The detector is triggered by a beam of light reflected from the pendulum arm just before impact.

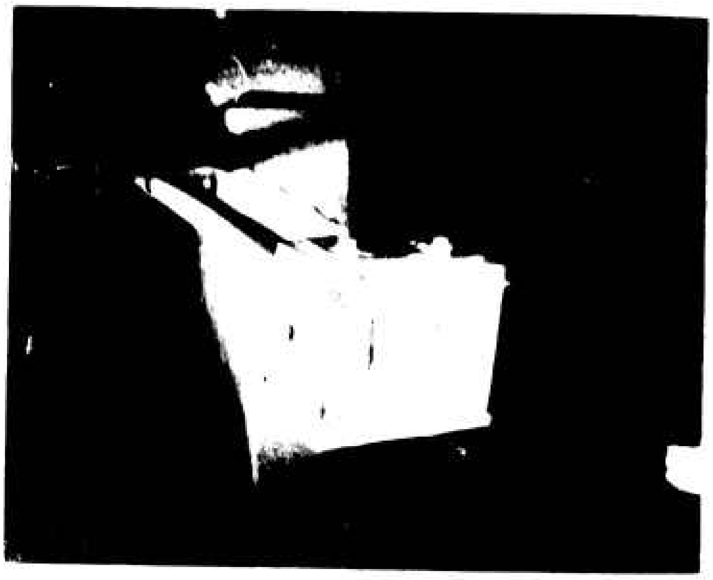


Figure 2. Location of Accelerometer.

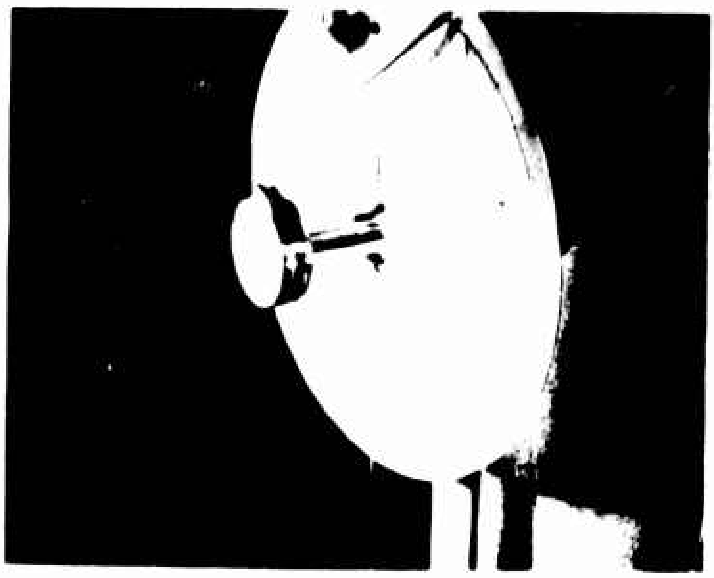


Figure 3. Location of Precision Potentiometer.

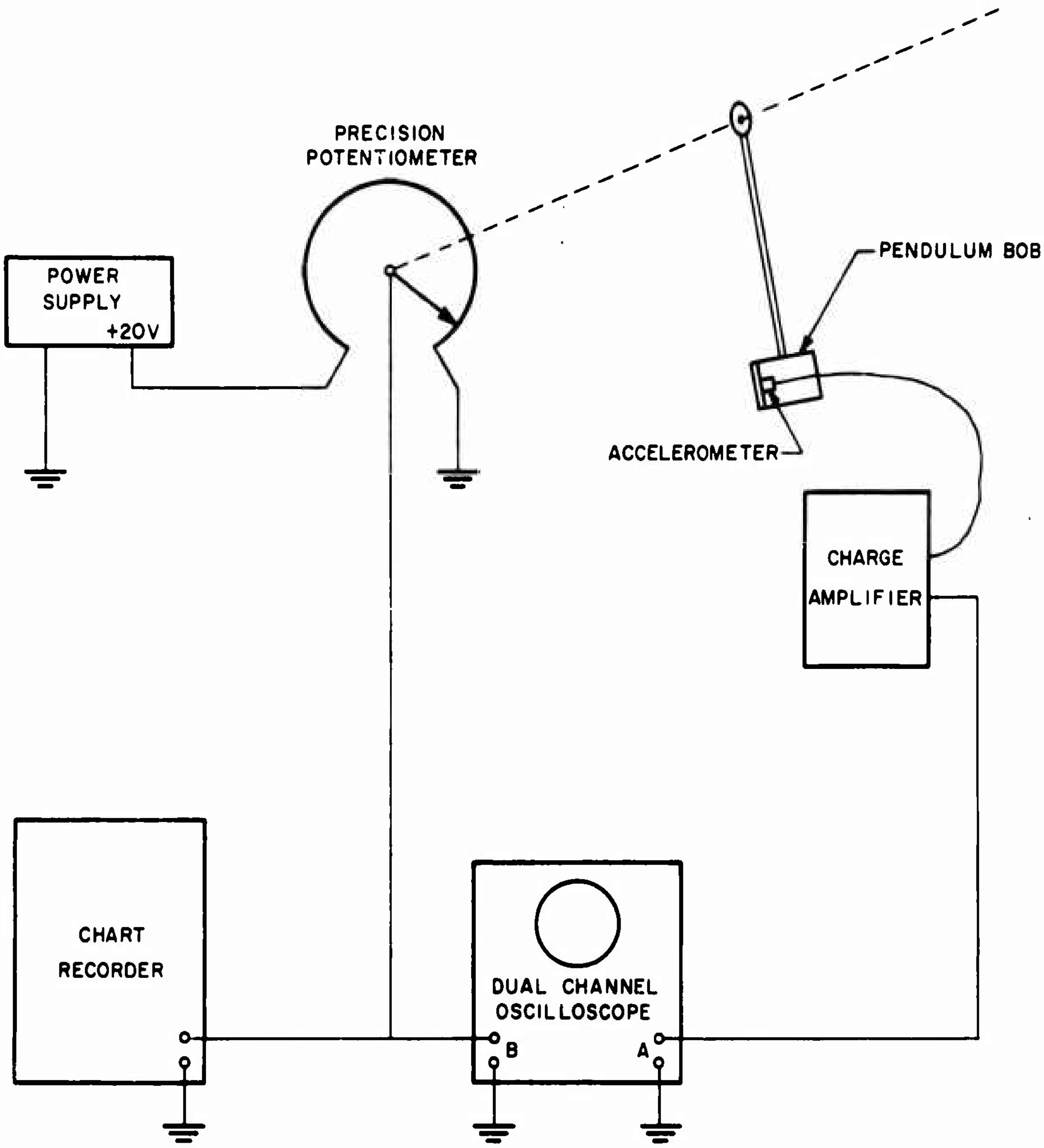


Fig. 4 Wiring Diagram of Pendulum Instrumentation

The impact tester, exclusive of the aforementioned modifications, has certain independent characteristics as listed in Table 2. The pendulum is released from either one of the two raised positions by a mechanical latch. The mass of the bob is varied with a special set of bolt-on weights.

Throughout all impact tests a closed circuit television camera with a video recorder was used to record the visual details of each impact. The video tape recorder was equipped with a slow motion and stop motion capability thus allowing reviewing and study of the action of the dilatant suspension-filled rubber bags during impact. However, due to the relatively low framing rate (60 frames per second) of the TV system the video recordings were of limited use.

TABLE 2

CHARACTERISTICS OF THE WIEDEMANN-BALDWIN MODEL SI-ID IMPACT TESTER

	Pendulum Bob with no added weights		Pendulum Bob with added weight	
Release Position	Low	High	Low	High
Weight of Pendulum Bob at Center of Percussion, lb.	17.9	17.9	31.3	31.3
Drop Height, Ft.	1.88	4.51	1.88	4.51
Impact Velocity, Ft/sec	11.0	17.0	11.0	17.0
Impact Energy, Ft-lb	33.61	80.63	58.77	140.98

3. INTERPRETATION OF TEST PARAMETERS

As discussed in the previous section the raw, unprocessed data for each impact test consist of a dual trace oscillograph showing deceleration and depth-of-penetration as a function of time, and the (maximum) angle of the rebound. The methods of determining the dependent variables from these data are described in the following sections.

3.1 Absorbed Energy

The amount of energy available for absorption by a test specimen is a function of the pendulum drop height and the weight of the bob as listed in Table 2. It is a precisely known quantity. If all available impact energy were absorbed by the test specimen no rebound of the pendulum would occur. In practice, all test specimens impacted during this study showed varying degrees of rebound.

As mentioned in Section 2 the rebound is measured in terms of angular rotation of the pendulum about its axis. The rebound energy in foot-pounds is calculated as:

$$E_R = 2.625\ W(1-\cos\theta) \tag{1}$$

where E_R is rebound energy (Ft-lbs),

2.625 is the length of the pendulum arm (ft.),

W is the weight of the pendulum bob (lbs),

and θ is the maximum angle of rebound (degrees).

The absorbed energy is then simply:

$$E_A = E_I - E_R \tag{2}$$

where E_I is the impact energy from Table 2 (Ft.lbs)

and E_A is the absorbed energy (Ft.lbs).

3.2 Depth of Penetration

The distance which the face of pendulum bob travels into a test specimen before it stops and begins its outward rebound is known as the depth of penetration. It is measured as shown in Figure 6 by extending a vertical line down from the initial impact point of the deceleration trace across the penetration trace. (The initial impact point is easily recognized by the abrupt discontinuity near the start of the deceleration trace.) This intersection gives the initial contact point of the pendulum face with the rubber bag. From the initial contact point to the maximum penetration point (lowermost excursion of penetration trace) the depth of penetration is measured graphically.

The unusual staircase shape of the penetration trace is due to the high gain of the Oscilloscope amplifier used to observe the electrical signal across the precision potentiometer. Each "step" actually represents the motion of the potentiometer wiper arm across one winding. Each winding, in turn, is equivalent to a movement of the pendulum face of 0.1". This, of course, is the limit of resolution for the penetration measurement. Spikes and small oscillations on the penetration trace were observed occasionally and are due to wiper noise and external transients.

Numerous studies[4,5,6] of human impact have indicated that the body is sensitive to at least three characteristics of the acceleration-time cycle to which it is subjected; these characteristics are peak force (deceleration), dwell time or period of force application and the initial rise time of the force which can be defined in a number of ways.

3.3 Peak Deceleration

The most obvious of the three parameters is the peak or maximum deceleration. Figure 5 is a typical example of an oscillograph of deceleration (and penetration) as recorded from the impacting of a dilatant suspension-filled rubber bag. Figure 6 is a graphic key to the interpretation of the oscillographs. It should be noted that peak deceleration is simply the maximum vertical excursion of the deceleration trace from the base or zero line. It is measured with a pair of draftman's dividers. Each vertical division (the grid lines) represents 20 g's.

3.4 Dwell Time

The dwell time is a measure of the duration of force application and is measured as shown in Figure 6. After the value of the peak deceleration is determined a horizontal line representing half this value is drawn across the deceleration trace as shown. Dwell time is the distance (time) between intersections.

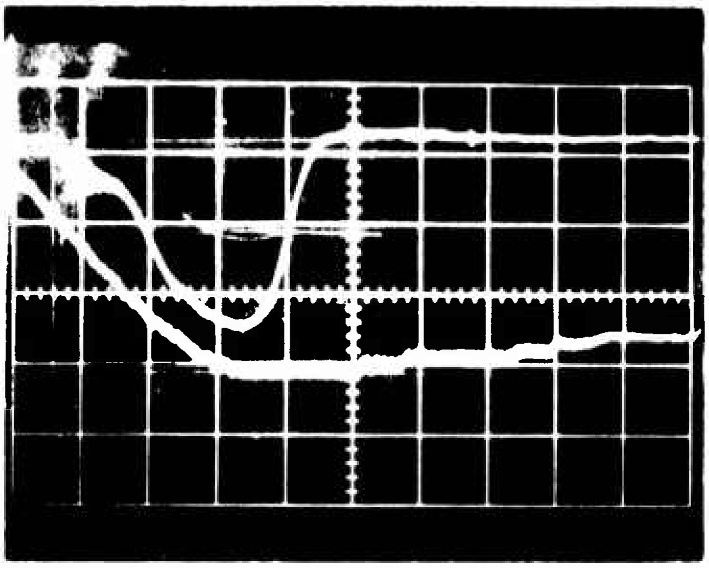


Fig. 5. Typical Oscillograph of Deceleration and Penetration of Impacting Pendulum Bob

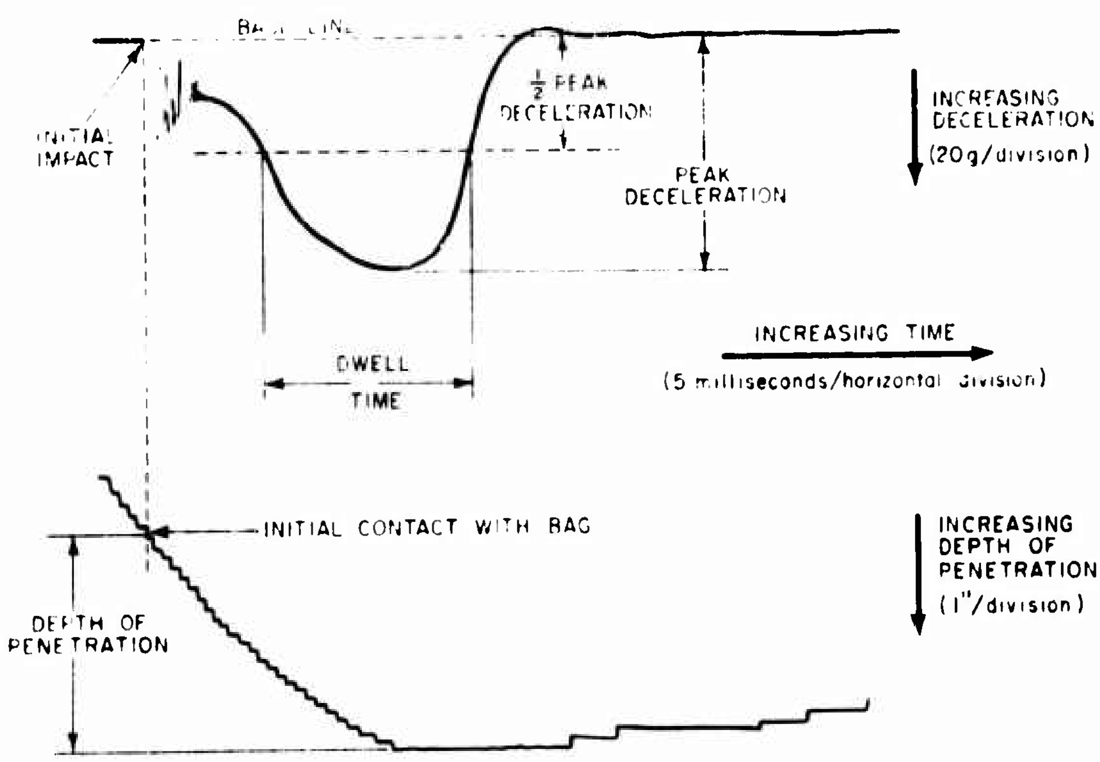


Fig. 6. Interpretation of Impact Oscillograph

3.5 Jerk

Jerk is defined as the rate of change of acceleration or deceleration with respect to time. The units are g/unit time and in this study they are g/millisecond. The value of jerk is determined by measuring the slope of deceleration trace at the desired point. For this study the maximum jerk was determined for both the deceleration and the portions of the trace rebound. In the first case the pendulum face is being slowed down or decelerated at an increasing rate by the action of the test specimen; thus, the jerk determined on that portion of the trace is called the initial jerk. In the second case the pendulum has been brought to a halt and is beginning to rebound and the "jerk" measured on this portion of the trace is called the rebound jerk. There is very little rebound in the case of the dilatant test specimens used in this study thus, the deceleration peak decays rapidly to zero. From a practical standpoint the initial jerk is a measure of the rise time of the force.

3.6 Impulse

Impulse may be defined as the integral of force over the time interval during which the force acts. With the experimental configuration of a swinging pendulum with a rigid backstop the impulse is equal to the sum of the initial momentum of the pendulum bob plus the rebound momentum of the bob. The units of momentum may be given as lb-sec so that impulse will be in lb-sec.

The initial momentum of the pendulum bob is easily calculated by

$$M_1 = \frac{W}{g} V_1 \tag{3}$$

where M_1 is the initial momentum (lb-sec)

W is the weight of the pendulum, bob (lbs)

g is acceleration constant of earth's gravity (Ft/sec^2)

and V_1 is the initial velocity of the pendulum bob at impact (Ft/sec).

The rebound momentum is calculated as

$$M_2 = \frac{W}{g} \sqrt{2g\ (1-\cos\theta)} \tag{4}$$

where M_2 is the rebound momentum (lb-sec),

and θ is the maximum angle of rebound (degrees)

The equation for impulse is then the summation of equations (3) and (4):

$$\text{Impulse} = \frac{W}{g} \left[V_1 + \sqrt{2g\ (1-\cos\theta)}\ \right] \tag{5}$$

It is of interest to note that the area under the deceleration trace (actually the area between the trace and its base line) when multiplied by the weight of the pendulum bob is equal to the impulse. Thus the accuracy of the dynamic measurements, acceleration/time, can be estimated by comparing this impulse with the calculated momentum charge. This comparison revealed that the two measurements agreed to within 8%.

3.7 Calculations

For each experiment the raw data was recorded on a data sheet, a sample of which is shown in Appendix A. After recording the raw data (rebound angle, weight, etc.) a programmable, desktop electric calculator was used to derive absorbed energy and impulse. Penetration, jerk, etc. were derived graphically using dividers and a protractor.

4. TEST SPECIMENS

The experimental plan called for the impacting of three different suspension densities of starch-salt water suspension. Globe Cornstarch #3005 was used for the solid, starch phase and a concentrated sodium chloride -water solution (26.5% by weight) for the liquid phase. The sodium chloride was used in the water to act as a preservative for the starch phase. The three concentrations of starch (47.5%, 50.0% and 52.5% by weight) suspension were mixed using a heated salt solution and poured into Tillotson #30 (40 oz.) rubber balloons, 0.020 in. wall. The filled rubber balloons or bags were sealed so that air was excluded. Each filled bag weighed about 3 lbs. and had a thickness of 3-1/4" along the impact axis.

Double thick (one bag inside another) bags were also filled with each starch suspension. The bags were always kneaded by hand before impact testing and water baths were used to obtain the high (110°F) and low (48°F) temperatures. Room temperature was assumed to be 80°F.

5. RESULTS AND DISCUSSION

Each concentration of starch-liquid suspension was impacted three times at each of the four energy levels listed in Table 2. This procedure was carried out at each of three bag temperatures (48°F, 80°F and 110°F) for both single and double bags. A total of 216 individual tests were run in the course of this study. Some miscellaneous tests were also run and will be discussed later.

All raw data were analyzed as discussed in Section 3 and tabulated as shown in the three tables of Appendix B. Each dependent parameter value listed in the tables of Appendix B is an average value found by averaging the results of the three impacts at any given test condition. Actually, results were very reproducible so that a high degree of confidence may be placed in the averaged values. Note that there are two vertical rows of data to the right of each impact condition. The upper row are data for a single bag while the lower row are double bag data. A small "d" to the upper right of the initial jerk values indicates that more than one distinct jerk maximum was noted.

The dependent parameters which were found to be of particular significance in this study were energy absorption efficiency, bag penetration, peak or maximum deceleration and initial jerk. The effect of the independent variables on each of these is discussed below.

5.1 Energy Absorption Efficiency

From the tables in Appendix B the energy absorption efficiency has been calculated for each test condition by dividing the absorbed energy by the impact energy. These quotients are expressed as percentages in Table 3. Examination of Table 3 suggests the following effects:

(a) Under all test conditions regardless of input energy, bag temperature or starch concentration the energy absorption efficiency is never below 96% and it is usually close to 99%.

(b) The double bags absorb slightly less energy than a single bag under the same conditions.

(c) As the concentration of the suspension is increased the energy absorption efficiency decreases.

(d) A bag temperature of 80°F (room temp.) generally yields the lowest energy absorption efficiency.

(e) As the impact energy is increased the energy absorption efficiency also increases.

Effects (a), (d) and (e) would be generally desirable for an impact absorbing cushion. Effect (b) indicates that as the wall thickness of the rubber bag is increased the energy absorption capability is reduced. Indirectly, it indicates that increasing the amount of elastic material, rubber, in the cushion increases the elastic rebound. It also suggests that in a practical impact cushion, provision may have to be made for the "venting" or expansion of the dilatant suspension, i.e. it cannot be tightly confined.

5.2 Bag Penetration

In order to study the effects of the impact energy upon bag penetration and other parameters the data presented in the tables of Appendix B have been "collapsed" or condensed in two steps. In the first step the effects of bag temperature have been extracted by averaging the data for each starch concentrations. Thus only the effects of temperature on an "average" mix are considered. In the second step the effects of bag temperature are eliminated by averaging the data of the first step, with respect to temperature. Thus an "average" concentration starch mix at an average temperature is considered. The double averaged data are presented in Table 4.

The penetration data for the single bag are plotted as a function of impact energy in Figure 7. It is clear that the depth to which the impacting pendulum penetrates a suspension-filled bag is dependent primarily on the impact energy. The velocity of the impact has little effect on the penetration. Of course, this is true only within limits. It has been verified experimentally, for instance, that the curve of Figure 7 comes close to intersecting the penetration axis at about 1.1". It should also be noted that these statements pertain to the balloon or rubber bag geometry used in these tests.

Other factors effecting the bag penetration (derived from the data in Appendix B) are as follows:

(a) Penetration of the double bag is less than that of the single bag at any given input condition.

(b) Increasing the starch concentration decreases the depth of penetration.

(c) Increasing the bag temperature increases the depth of penetration except at the highest energy (140 Ft-lbs) input.

None of these effects seem detrimental to the use of a dilatant suspension as an impact cushion. They do indicate that the thickness of the cushion would have to be proportional to the expected impact energies.

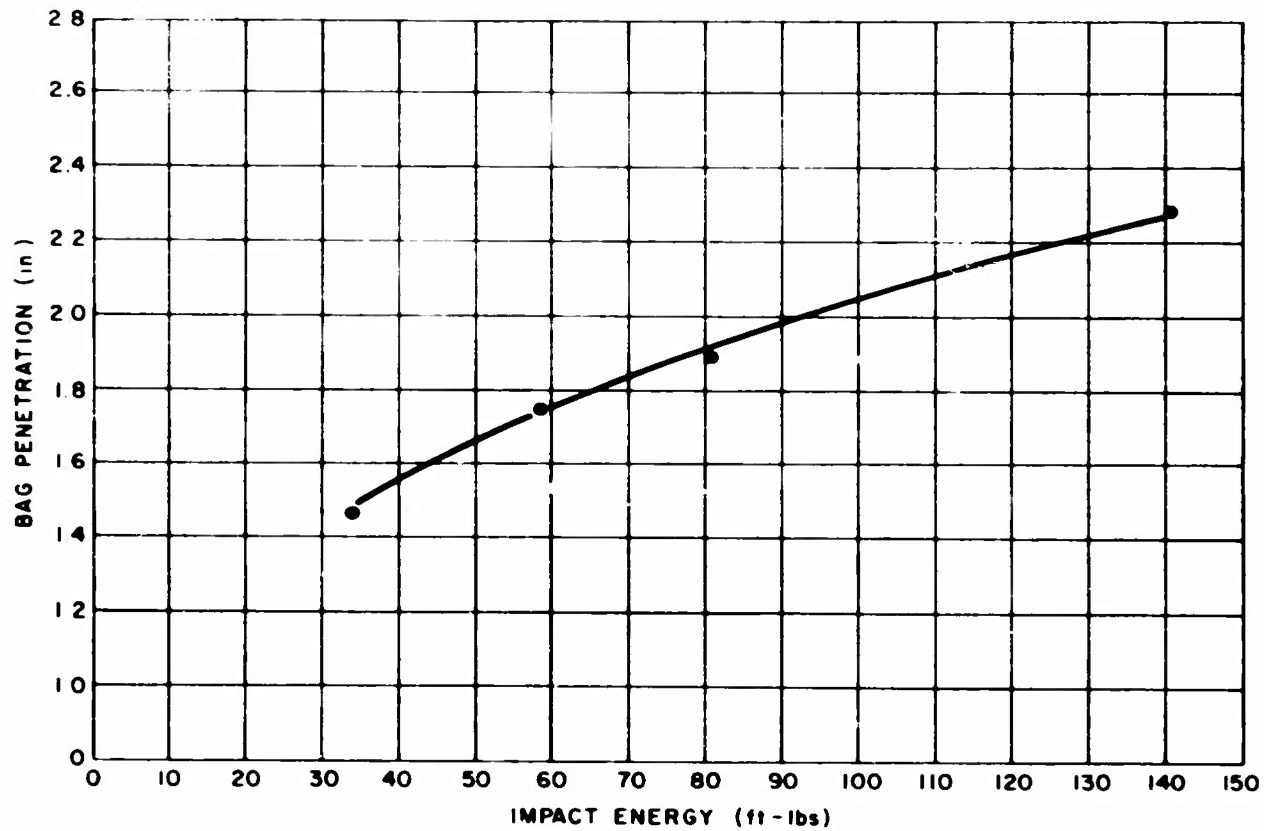


Fig. 7 Average Bag Penetration As a Function of Impact Energy
(Single Bag)

TABLE 3

ENERGY ABSORPTION EFFICIENCY (%)
FOR VARIOUS TEST CONDITIONS

		SUSPENSION CONCENTRATION								
Impact Energy (Ft-lbs)	Bag Type	47.5% Starch Bag Temp.			50.0% Starch Bag Temp.			52.5% Starch Bag Temp.		
		48°F	80°F	110°F	48°F	80°F	110°F	48°F	80°F	110°F
33.61	single	99.4	99.5	99.4	99.0	98.4	99.4	98.0	96.8	98.1
	double	99.3	98.9	99.2	98.6	97.8	98.7	97.8	96.4	97.9
58.77	single	99.8	99.7	99.7	98.9	98.7	99.4	98.7	96.6	98.6
	double	99.7	99.7	99.2	98.7	97.9	98.9	98.1	96.5	98.5
80.64	single	99.7	99.4	99.7	99.3	98.8	99.5	99.0	96.4	99.1
	double	99.6	99.5	99.6	99.2	98.1	99.2	99.0	95.8	98.9
140.98	single	99.9	99.8	99.7	99.5	98.9	99.7	99.2	97.8	99.5
	double	99.7	99.8	99.4	99.5	98.5	99.5	99.1	97.2	99.3

TABLE 4

AVERAGE BEHAVIOR OF STARCH SUSPENSION
AS A FUNCTION OF IMPACT ENERGY

	Impact Energy (Ft.lbs)	Bag Type	Bag Penetration (in.)	Peak Deceleration (g)	Jerk g/msec)
Impact Velocity = 11 ft/sec	33.64	single	1.46	44	6.1
		double	1.42	45	6.4
	58.77	single	1.75	37	4.5
		double	1.70	39	4.9
Impact Velocity = 17 ft/sec	80.64	single	1.89	70	12.3
		double	1.85	72	11.8
	140.98	single	2.28	60	8.3
		double	2.20	62	9.1

5.3 Peak Deceleration and Jerk

The principle aim of this program has been to characterize the deceleration or force response of the dilatant suspension to impact. From Table 4 it can be seen that both the peak deceleration and initial jerk are functions of impact velocity as well as the impact energy. Indeed, increased velocity produces higher peak deceleration and jerk while increased energy at a fixed velocity yields markedly lower peak deceleration and jerk. This result supports the contention that dilatant systems offer a range of responses to impact that are not attainable with conventional cushion materials.

The following hypothesis is offered to explain this behavior. As the shear rate in a dilatant suspension is increased the viscosity or resistance to shearing increases. Thus, as impact velocity increases the resistance to the impacting surface is increased giving higher values of deceleration and jerk. However, if only the impacting energy is increased while holding the velocity fixed then viscosity remains relatively fixed and the suspension offers a constant resistance to penetration. As the energy increases at constant velocity the momentum of the impacting pendulum increases. The increasing momentum is, therefore, being opposed by a constant force and hence the retardation or deceleration produced per unit penetration is less. This of course leads to lower maximum deceleration but increased dwell time.

Examination of the dwell times in Appendix B confirms that for a fixed velocity the higher energy yields longer dwell times.

The increase in peak force with increasing impact velocity is probably limited by the force required to sustain crushing of the entire volume of the pseudo-solid.

Other factors affecting the peak deceleration and initial jerk are:

(a) A double bag yields higher peak decelerations and generally higher values of jerk.

(b) Increasing the concentration of starch causes only a slight increase in the peak deceleration and slight to moderate increases in the jerk values.

(c) The effect of temperature on peak deceleration is rather unusual and is best illustrated by the graph of Figure 8. It may be seen that the greatest values of peak deceleration at any given energy level occur in the vicinity of room temperature (80°F). This unusual behavior is further illustrated in the set of oscillographs in Figure 9. The same type of relationship also exists between the bag temperature and the initial jerk although it is not plotted.

Such behavior is probably due, at least in part, to the effect of temperature on the elastic properties of the container bags.

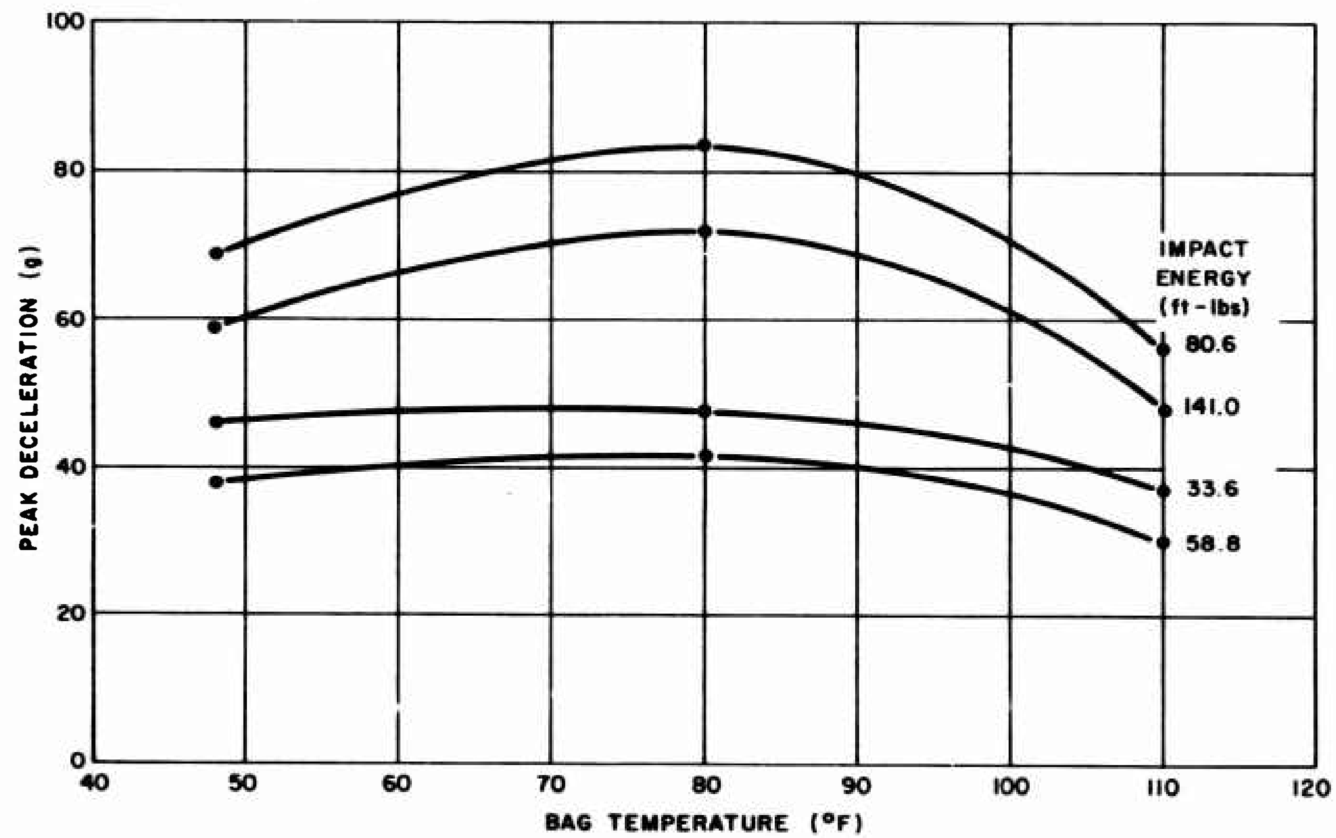
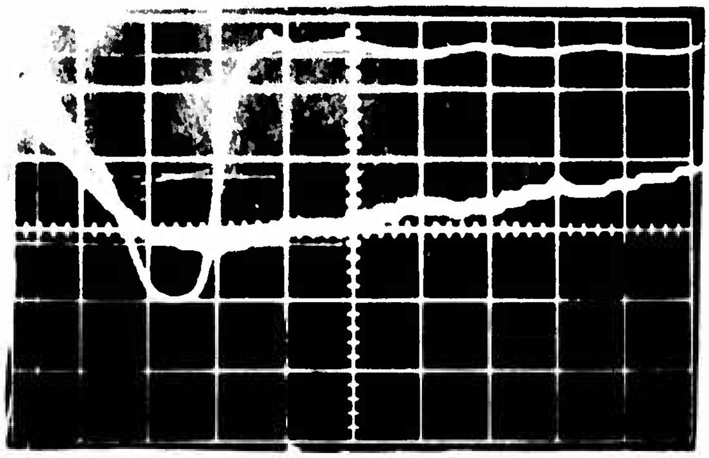
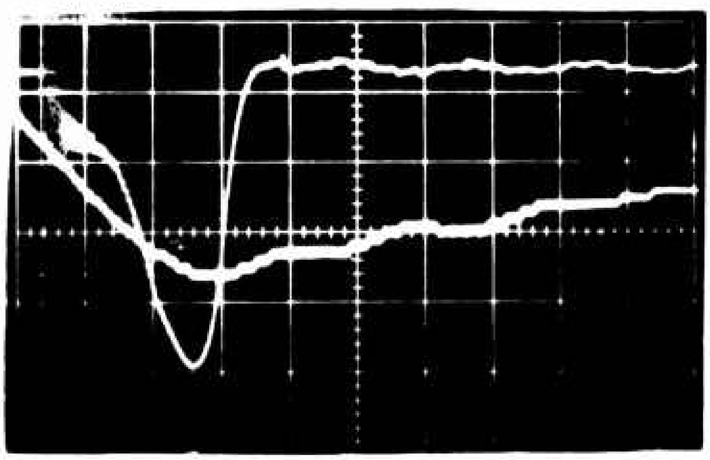


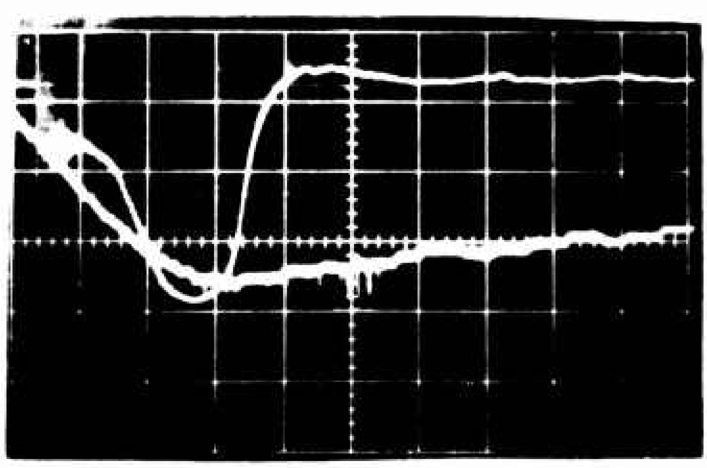
Fig. 8 Behavior of Peak Deceleration As a Function of Bag Temperature (Average Mix)



Bag Temperature = 45°F



Bag Temperature = 80°F



Bag Temperature = 110°F

Figure 9. Dynamic Behavior of 50.0% Starch Mix at Various Bag Temperatures. (Impact Energy = 80.6 Ft.-lbs.)

Figure 10. Impact Pendulum with 1 cm Radius Impacter Attached.

Small Radius Impact Head

A few impact tests were performed using a steel impact probe as shown in Figure 10. The radius of the protruding tip is 1 centimeter and it protrudes 2-1/2" from the normal surface of the impact plate into which it screws. The purpose of these tests was to study the manner in which impacts of certain small radius parts of the human body (elbows, nose, hip bones, etc.) could be absorbed. These tests were only partially successful because the probe penetrated the bags so far that the flat impacting surface to which the probe was attached also contacted the bag. Figure 11 shows typical deceleration and penetration traces. The abrupt dip in the deceleration trace indicates the point at which the flat impact plate contacted the bag. No rebound was observed in these tests. The initial jerk before the flat impact plate contacted the bag was less than 1 g/msec (for a 50.0% starch concentration at 80°F, with an input energy of 33.6 ft-lbs). This is a relatively small value of jerk and it appears that if the depth of bag had been great enough the peak deceleration would have been less than 15g.

Other Test Materials

A number of other materials such as polyurethane foams and packing materials were used as test specimens for possible comparison with the starch-water dilatant suspension. The results of these tests are presented in Table 5. Only one impact energy was used since a limited quantity of test specimens were available and were not always reusable (i.e. they did not recover from the impact). Furthermore, since the shape of the impacted surface of the non-dilatant test specimens was flat whereas the dilatant suspension-filled rubber bags had a somewhat rounded shape it was felt that detailed comparisons would not be justified. Distinct differences in the behavior of the two types of material may be noted however by comparing tables 4 and 5. The air bubble packing material and the closed-cell polyurethane foam show low energy absorption efficiencies; the compressed polyurethane foam while showing a small depth of penetration gives a high initial jerk; and the open-cell polyurethane foam shows a large depth of penetration. The polyurethane foams also exhibited peak decelerations significantly lower than that of the dilatant suspensions under the same impact conditions. This is due to the greater elastic reaction of the foams. This elastic response also gives rise to very undesirable rebound and lowered energy absorption efficiency.

One other test of interest involved impact of a rubber container filled only with water. The water bag offered only insignificant resistance to the pendulum which penetrated it completely and struck the back plate sharply. This demonstrated rather dramatically the poor energy absorbing efficiency of a simple low viscosity fluid in an elastic container.

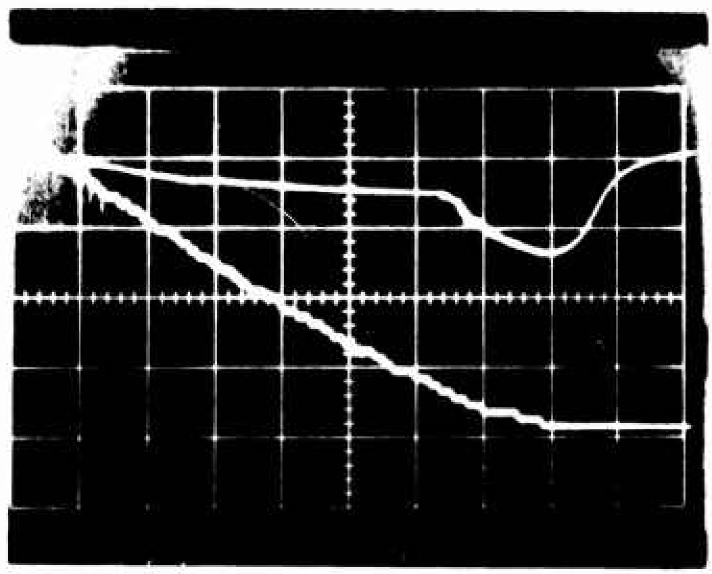


Figure 11. Dynamic Behavior of 50.0% Starch Suspension with 1 cm Radius Impact Head. (80°F, 33.6 ft.-lbs., Single Bag)

TABLE 5

BEHAVIOR OF VARIOUS NON-DILATANT IMPACT ABSORBERS

(Impact Energy = 33.6 ft-lbs)

Impact Absorbing Material	Energy Absorption Efficiency (%)	Penetration of 3" Specimen (inches)	Peak Deceleration (g)	Initial Jerk (g/msec)
Air-Bubble Packing Mat'l	52.7	2.40	43	3.9
Closed-cell Polyurethane Foam	81.3	1.44	29	5.3
Compressed Polyurethane Foam	90.0	0.90	44	17.3
Open-cell Polyurethane Foam	89.5	2.40	35	3.6
"Average" Dilatant Suspension	>97	1.46	44	6.1

Fatigue of Dilatant Suspension

There had been some concern at the start of this project that repeated impacting of the dilatant suspensions at various temperatures would cause deterioration or fatigue of the dilatant properties. After as many as 38 impacts at various temperatures and energies no changes could be detected in the deceleration/time traces for any of the suspensions tested.

6. CONCLUSIONS

The impact behavior of the dilatant suspensions may be characterized as follows:

a. The three-inch cushion thickness was sufficient to fully arrest the flat impactor for all impact conditions examined.

b. The peak deceleration and jerk increased with impact velocity but decreased with increasing impact energy at constant impact velocity.

c. The elastic rebound was minimal indicating a high degree of energy absorption presumably due to crushing of the pseudo-solid.

The impact absorbing characteristics of the suspensions proved to be quite insensitive to changes in temperature and concentration for the ranges examined. Increasing the amount of elastic restraint, double rubber bag, had the undesirable effect of increasing peak deceleration jerk and rebound.

Other materials that exhibit a greater elastic response can produce lower peak deceleration and jerk than dilatant suspensions but only at the price of increased elastic rebound which leads to overshoot and increased injury rates in ejection seat cushion applications. In addition, of course, only dilatant systems automatically adjust their response according to the loading rate. It is also interesting to note that a dilatant system is the only type of system which can absorb energy by the efficient crushing process and which can also reconstitute itself for repeated subsequent use. Such behavior might have applications, for example, in the damping of large gun recoil.

In summary it can be stated that dilatancy can readily be achieved during impact and that in the dilatant condition the pseudo-solid exhibits impact absorbing properties that are both superior to conventional materials and easily varied to suit specific requirements. This success, however, should be viewed as only a first step in the exploitation of non-Newtonian fluid systems for use as impact absorbers. It is recommended that other dilatant systems be evaluated and also prototype cushions be fabricated and tested using conventional techniques (dummies, rocket sleds, etc.) and by comparison with currently used cushion materials.

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APPENDIX A

Sample Data Sheet

DATA SHEET

TEST NO.:______________________ Date:______________________

BAG MATERIAL:______________________

Composition of
Absorbing Material:______________________

____

____

History:______________________

____

BAG:

Mass ______________________

Temperature (°F) ______________________

Thickness (in.) ______________________

PENDULUM:

Weight (lbs) ______________________

Initial Height (ft.) ______________________

Final Height (ft.) ______________________

Rebound Angle (°) ______________________

Impact Velocity ______________________

Impact Momentum (lb.sec.) ______________________

Rebound Momentum (lb.sec.) ______________________

Impulse (lb.sec.) ______________________

Initial Energy (ft.lbs.) ______________________

Final Energy (ft.lbs.) ______________________

Absorbed Energy (ft.lbs.) ______________________

Penetration (in.) ______________________

Dwell Time (millisec.) ______________________

Max. Deceleration (g's) ______________________

Max. Jerk (g/sec.) ______________________

COMMENTS:______________________

____

____

APPENDIX B

Tabulated Data

Bag Temperature - 48°F

Mix No.	Impact Energy (ft.lbs.)	Impact Velocity (ft/sec.)	Weight (lbs)	Impulse (lb.sec)	Absorbed Energy (ft.lbs)	Bag Pene. (in.)	Max Decel. (g)	Dwell (msec)	Jerk (g/ms) IN	Jerk (g/ms) OUT	Test No.
	33.61	11.0	17.9	6.586	33.414	1.44	45	8.3	6.4	15.7	13
				6.649	33.357	1.73	44	8.4	6.7	13.1	15
#1	58.77	11.0	31.3	11.157	58.656	1.87	38	10.0	4.1[d]	12.3	19
47.5%				11.359	58.538	1.81	38	10.0	4.1	9.9	21
Starch	80.64	17.0	17.9	9.897	80.474	1.95	68	8.1	9.9[d]	32.6	14
				9.986	80.399	1.99	68	8.0	11.0	28.5	16
	140.98	17.0	31.3	16.836	140.942	2.53	59	10.0	6.7[d]	20.6	20
				17.194	140.773	2.37	57	9.8	7.8[d]	18.8	22
	33.61	11.0	17.9	6.710	33.293	1.40	44	8.9	5.5	13.1	49
				6.826	33.158	1.23	45	8.2	5.2	12.6	51
#2	58.77	11.0	31.3	11.826	58.104	1.53	36	10.3	4.8[d]	11.1	55
50.0%				11.903	58.010	1.52	40	9.3	5.3[d]	14.0	57
Starch	80.64	17.0	17.9	10.209	80.147	1.75	71	8.0	11.6[d]	28.5	50
				10.324	79.982	1.60	68	8.2	9.4[d]	32.6	52
	140.98	17.0	31.3	17.614	140.406	2.13	54	10.5	8.6[d]	20.6	56
				17.692	140.318	1.95	58	10.0	9.4[d]	20.6	58
	33.61	11.0	17.9	6.986	32.930	1.10	48	8.2	8.0	19.0	85
				7.040	32.844	1.03	47	8.6	8.0[d]	19.0	87
#3	58.77	11.0	31.3	11.919	57.990	1.33	39	10.0	6.1[d]	11.4	91
52.5%				12.183	57.620	1.48	36	10.8	5.1[d]	8.6	93
Starch	80.64	17.0	17.9	10.386	79.883	1.40	69	8.0	22.9[d]	38.1	86
				10.404	79.853	1.57	65	9.0	19.0[d]	30.0	88
	140.98	17.0	31.3	17.910	140.039	1.93	63	10.4	10.3[d]	28.6	92
				18.096	139.761	2.00	56	10.6	12.5[d]	23.0	94

Bag Temperature - Room (≈ 80°F)

Mix No.	Impact Energy ft.lbs.)	Impact Velocity (ft/sec.)	Weight (lbs)	Impulse (lb.sec)	Absorbed Energy (ft.lbs)	Bag Pene. (in.)	Max. Decel. (g)	Dwell (msec)	Jerk (g/ms) IN	Jerk (g/ms) OUT	Test No.
	33.61	11.0	17.9	6.532	33.457	1.79	46	8.5	5.7	14.9	1
				6.746	33.255	1.69	44	8.4	5.9	14.0	3
#1	58.77	11.0	31.3	11.283	58.587	1.97	40	9.7	4.0	11.6	25
47.5%				11.218	58.625	1.81	40	8.9	4.3	11.6	27
Starch	80.64	17.0	17.9	9.621	80.618	2.20	71	7.9	8.6	35.0	2
				10.021	80.365	2.12	73	7.8	8.6	32.0	4
	140.98	17.0	31.3	17.055	140.854	2.45	67	8.1	7.5	30.0	26
				17.240	140.742	2.42	68	8.0	7.2	25.2	28
	33.61	11.0	17.9	6.897	33.062	1.42	46	8.5	6.4	12.3	37
				7.031	32.858	1.33	51	7.5	7.8	17.3	39
#2	58.77	11.0	31.3	11.950	57.951	1.63	42	8.7	4.9	12.3	61
50.0%				12.261	57.498	1.60	48	8.0	6.7	14.9	63
Starch	80.64	17.0	17.9	10.483	79.713	1.90	84	6.5	14.0	32.6	38
				10.776	79.103	1.73	90	6.0	13.1	38.1	40
	140.98	17.0	31.3	18.174	139.635	2.11	72	7.9	9.0	32.6	62
				18.578	138.879	2.12	81	7.2	11.6	32.6	64
	33.61	11.0	17.9	7.208	32.538	1.23	53	7.8	10.3	16.3	73
				7.279	32.394	1.24	54	7.2	9.4	19.0	75
#3	58.77	11.0	31.3	12.664	56.762	1.47	44	8.4	6.7[d]	11.6	97
52.5%				12.711	56.666	1.40	49	7.6	7.5	14.0	99
Starch	80.64	17.0	17.9	10.935	78.707	1.58	97	6.0	19.0	38.2	74
				11.138	78.136	1.60	98	6.0	16.0[d]	38.1	76
	140.98	17.0	31.3	18.964	138.000	1.80	80	7.4	13.1	28.5	98
				19.272	137.187	1.73	92	6.7	13.1[d]	38.1	00

Bag Temperature - 110°F

Mix No.	Impact Energy (ft.lbs.)	Impact Velocity (ft/sec.)	Weight (lbs)	Impulse (lb.sec)	Absorbed Energy (ft.lbs)	Bag Pene. (in.)	Max. Decel. (g)	Dwell (msec)	Jerk (g/ms) IN	Jerk (g/ms) OUT	Test No.
	33.61	11.0	17.9	6.545	33.406	1.89	36	9.8	4.0	9.4	7
				6.711	33.294	1.83	35	10.1	4.0	9.4	9
#1	58.77	11.0	31.3	11.281	58.588	2.44	28	12.1	2.3	6.9	31
47.5%				11.686	58.258	2.25	29	12.0	2.6	6.2	33
Starch	80.64	17.0	17.9	9.879	80.488	2.43	51	10.3	6.4	14.9	8
				9.960	80.423	2.47	54	9.9	7.2	14.9	10
	140.98	17.0	31.3	17.117	140.821	3.00	46	11.2	4.9	14.0	32
				17.366	140.645	2.75	42	10.4	6.2	14.9	34
	33.61	11.0	17.9	6.613	33.391	1.65	39	9.5	4.8	10.4	43
				6.817	33.169	1.41	42	9.0	5.3	11.0	45
#2	58.77	11.0	31.3	11.561	58.377	1.93	33	11.1	3.9	9.0	67
50.0%				11.841	58.086	1.77	34	10.9	4.4[d]	9.4	69
Starch	80.64	17.0	17.9	10.013	80.373	2.00	63	8.8	8.2	20.6	44
				10.324	79.982	1.86	70	7.5	10.4	25.2	46
	140.98	17.0	31.3	17.257	140.730	2.40	52	10.3	7.2[d]	20.6	68
				17.739	140.262	2.22	54	10.3	6.9[d]	18.8	70
	33.61	11.0	17.9	6.915	33.037	1.27	39	10.0	4.1[d]	10.3	79
				7.022	32.873	1.30	41	9.4	5.2[d]	11.4	81
#3	58.77	11.0	31.3	11.919	57.990	1.58	32	12.0	3.5[d]	8.2	103
52.5%				11.935	57.970	1.68	32	11.0	3.9	7.2	105
Starch	80.64	17.0	17.9	10.360	79.926	1.83	56	9.8	10.3[d]	19.0	80
				10.475	79.729	1.70	61	9.8	11.4[d]	22.9	82
	140.98	17.0	31.3	17.599	140.442	2.16	50	11.6	7.5	18.8	104
				17.848	140.124	2.24	50	11.2	7.2	14.9	106

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13 ABSTRACT

The impact absorbing properties of starch/brine dilatant suspensions were characterized with an instrumented, pendulum-type impact tester. The starch concentrations were varied between 47.5 and 52.5% and sealed in heavy rubber bags of varying thickness. The temperature of the filled rubber bags was varied between 45° and 110°F. Impacting energies ranged between 30 and 141 ft-lbs with velocities of 11 and 17 ft/sec. The dilatant suspensions were found to be highly efficient and reusable energy absorbers under all test conditions. Impactor penetration, peak deceleration, and jerk varied depending on the impact energy input, impact velocity, bag wall thickness, and, to a lesser extent, starch concentration and temperature. The filled bags readily conform to the shape of a 1 cm radius impactor and yield relatively low peak deceleration and jerk. There was no noticeable deterioration of the dilatant properties as a result of temperature cycling and repeated impacts.

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
DILATANT MATERIALS ENERGY ABSORPTION SEAT CUSHIONS IMPACT SHOCK ACCELERATION						

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